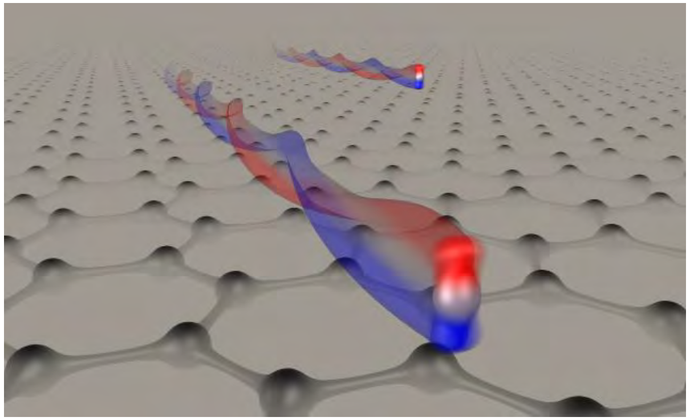
The University of Manchester

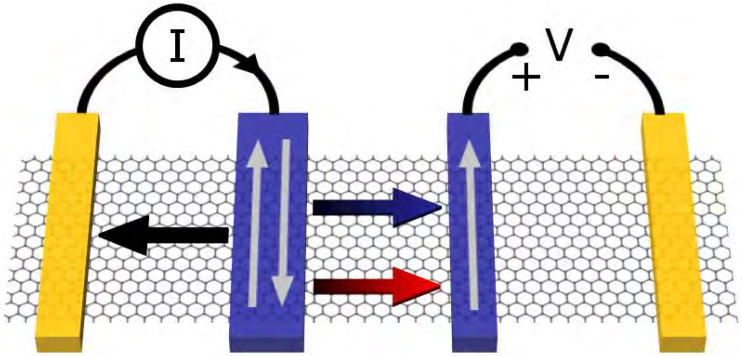
Novel architectures for graphene spintronics

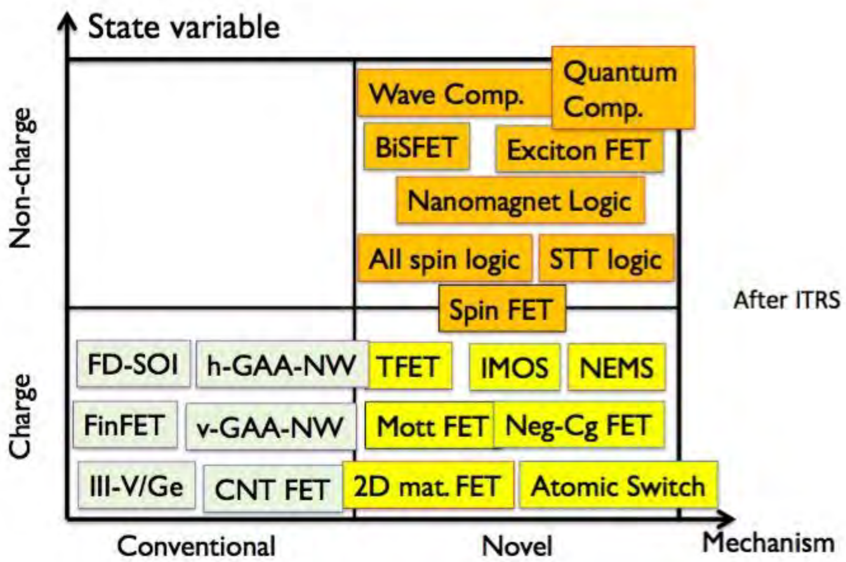


Ivan Jesus Vera-Marun

Nonlocal spin geometry

Novel spin functionality in future electronics (ITRS)
Separate charge from other degrees of freedom
All-electrical approach





What can we learn?

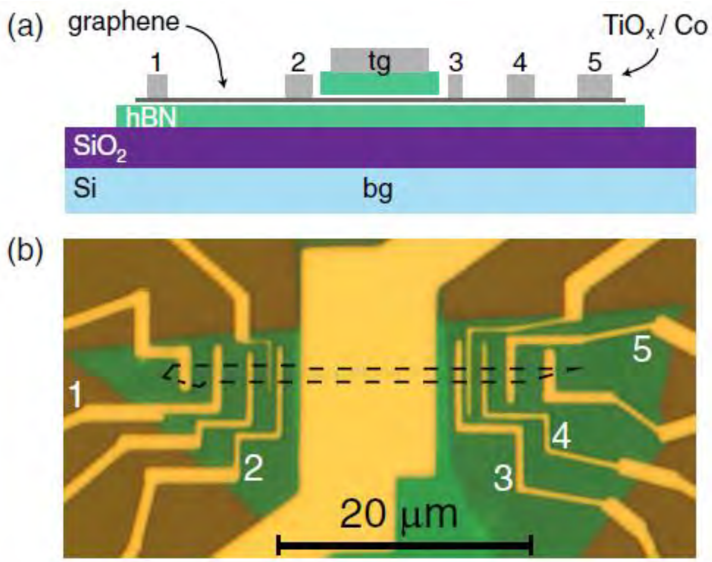
Double-gated encapsulated bilayer

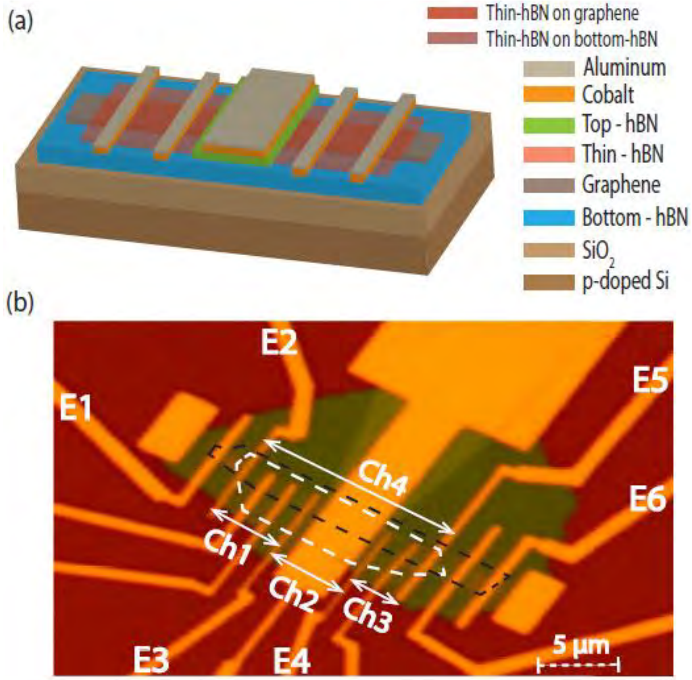
Nature of spin relaxation + spin FET action

Vertical spin transport junctions

Probe proximity to ferromagnetic metals

State of the art: Groningen group



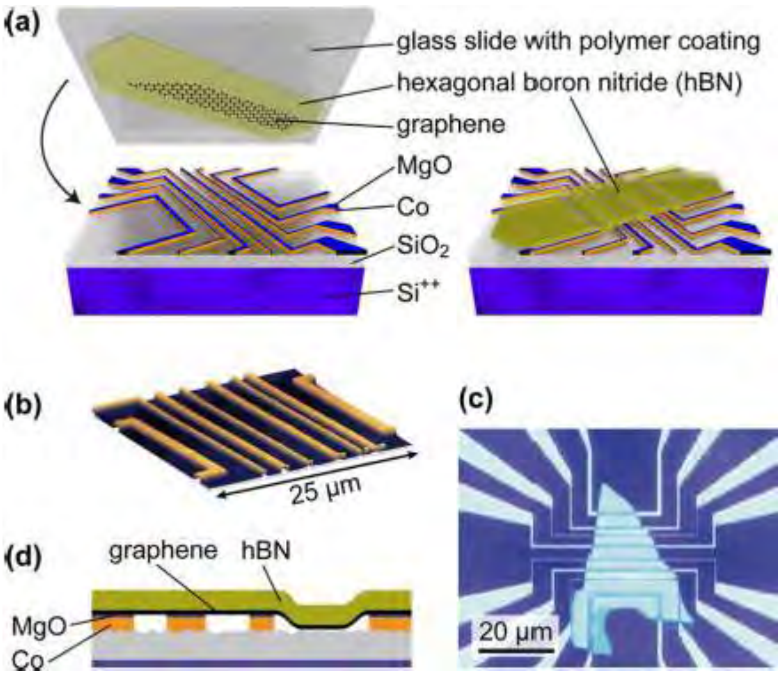


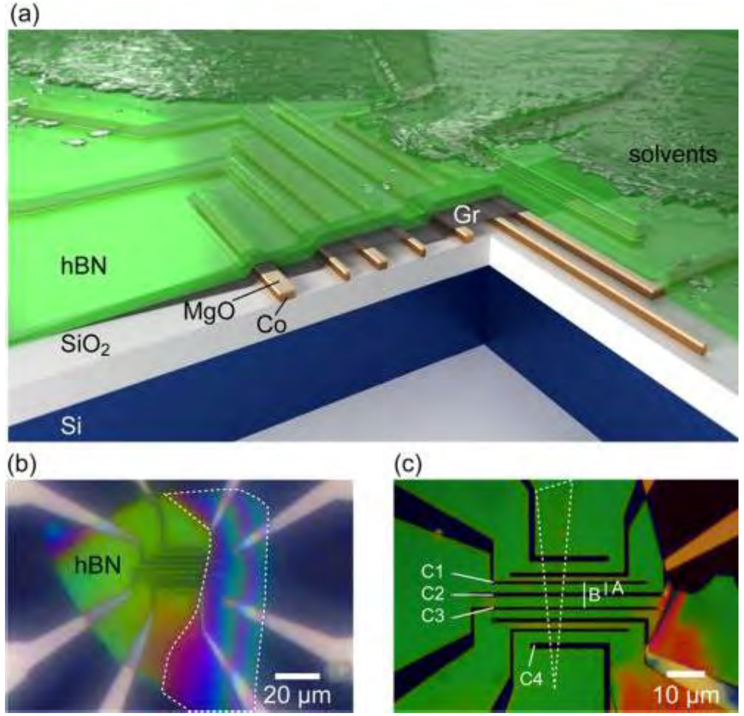
- Partially encapsulated graphene [1]
- μ ≈ 23000 cm^2/Vs at 4.2 K
- Outer regions affect spin transport

- First fully encapsulated w SL h-BN [2]
- μ ≈ 8600 cm^2/Vs at RT
- Low yield (only one made)

*[1] M.H.D. Guimarães, P.J. Zomer, J. Ingla-Aynés, J.C. Brant, N. Tombros, and B.J. van Wees, Phys. Rev. Lett. **113**, 086602 (2014)*
*[2] M. Gurram, S. Omar, S. Zihlmann, P. Makk, C. Schönenberger, and B. J. van Wees, Phys. Rev. B **93**, 115441 (2016)*

State of the art: Aachen group





- Bottom –up fabrication technique
- μ ≈ 20000 cm^2/Vs at RT (best quality)
- MgO tunnel barrier exposed after deposition, fixed architecture

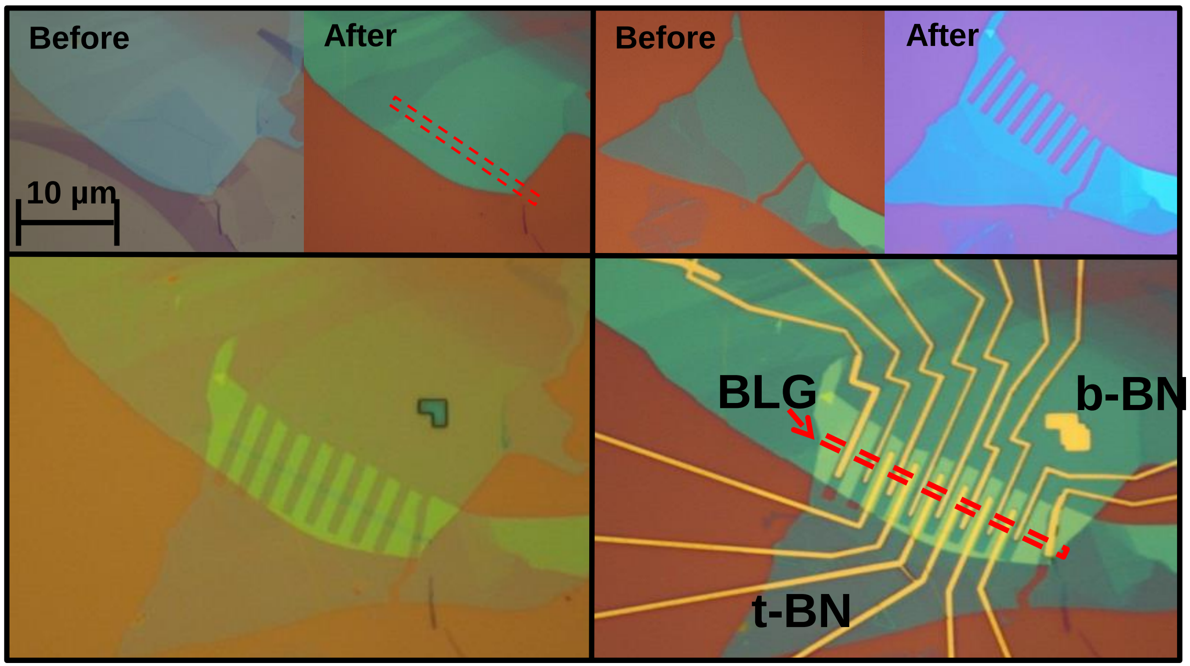
M. Drögeler, F. Volmer, M. Wolter, B. Terrés, K. Watanabe, T. Taniguchi, ... and B. Beschoten, Nano Lett. ***14****, 6050 (2014)*
M. Drögeler, C. Franzen, F. Volmer, T. Pohlmann, L. Banszerus, M. Wolter, ... and B. Beschoten, Nano Lett. ***16****, 3533 (2016)*

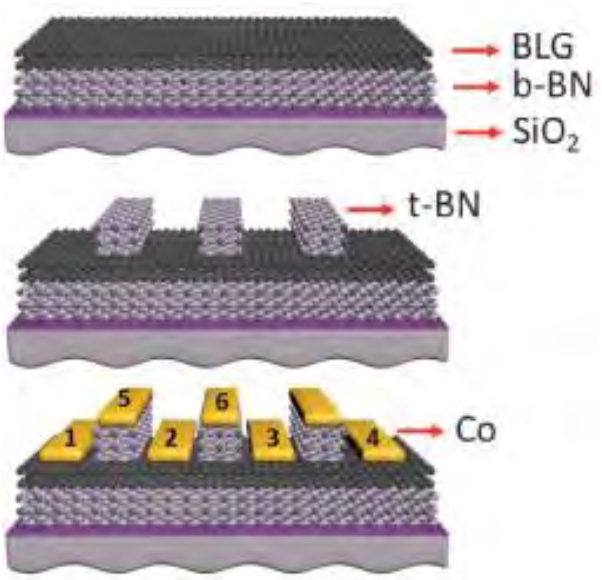
Novel high-quality architecture

Flexible achitecture based on pre-patterned top hBN

Series of fully encapsulated regions + contact regions

Large diffusion lengths (6 μm @ RT, 10 μm @ 2 K)





A. Avsar, I. J. Vera-Marun, J. Y. Tan, G. K. W. Koon, K. Watanabe, T. Taniguchi, S. Adam, and B. Ozyilmaz, "Electronic Spin Transport in Dual-Gated Bilayer Graphene," NPG Asia Materials 8, e274 (2016)

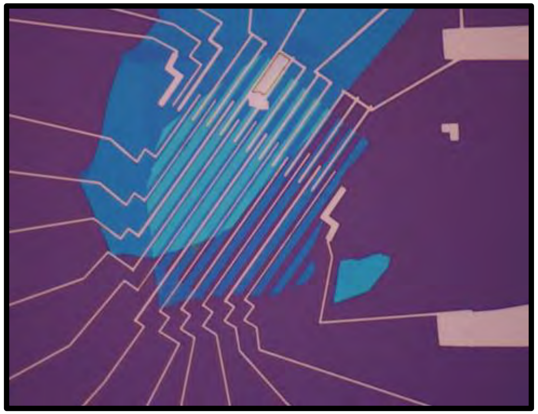
Effect of hBN encapsulation

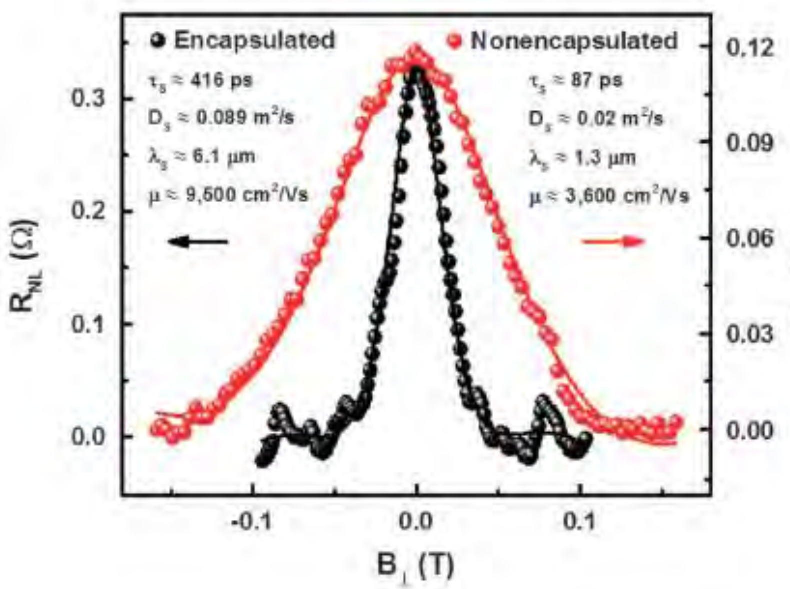
Non-encapsulated: similar to BLG on SiO_2

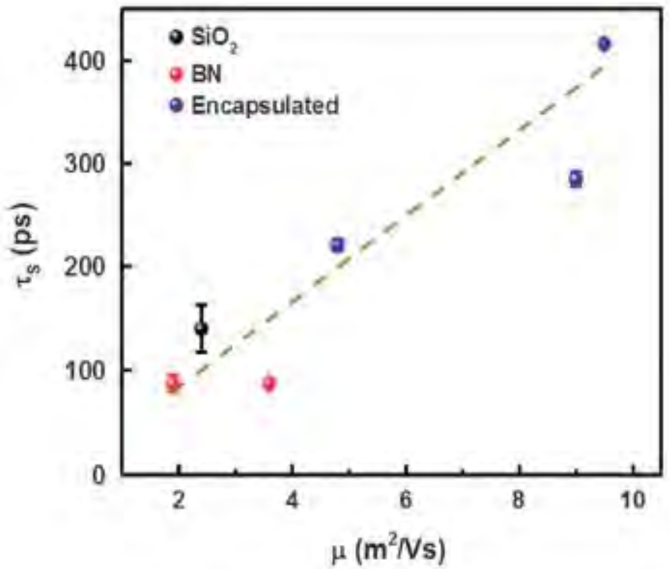
→ substrate issues such as roughness & charged impurities not the main source of spin relaxation

Encapsulated: 5x spin lifetime, 4x spin signal

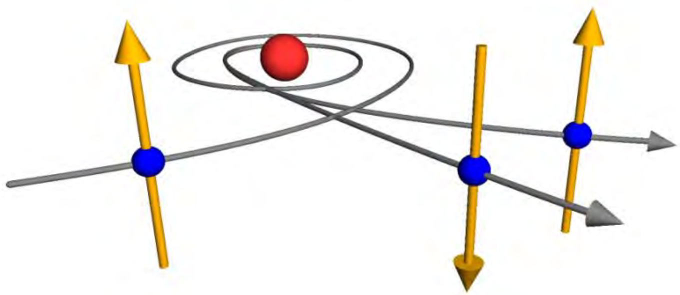
→ Protection against residues during fabrication
→ Contacts not the main limitation



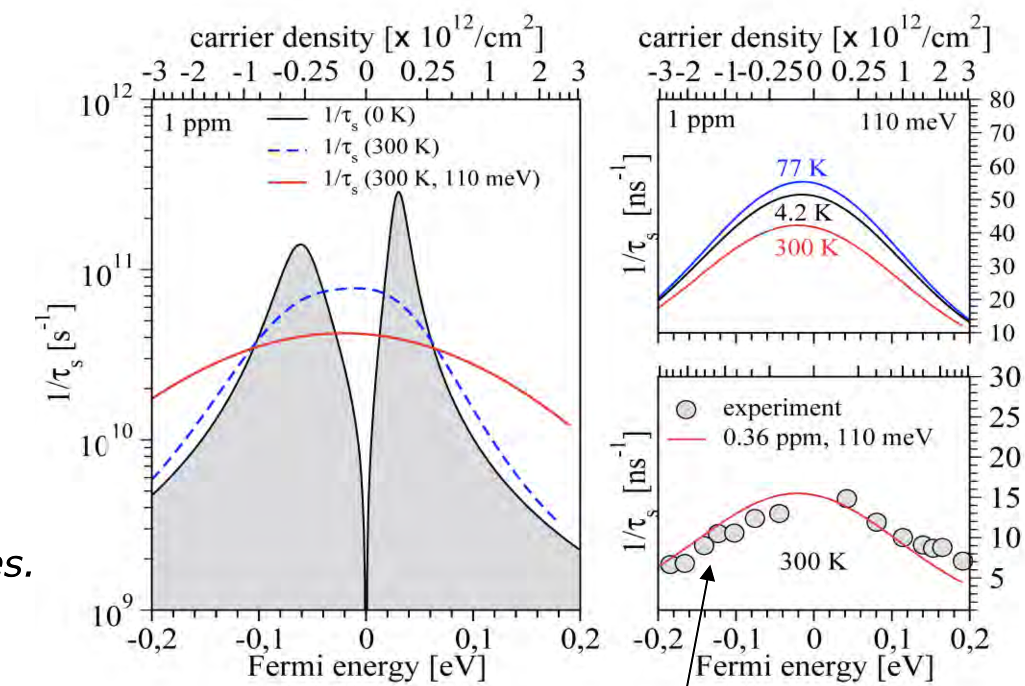




Recent spin relaxation mechanism: resonant impurity scattering



Kochan, D., Gmitra, M. & Fabian, J. Spin Relaxation Mechanism in Graphene: Resonant Scattering by Magnetic Impurities. Phys. Rev. Lett. ***112,*** *116602 (2014).*



Non-monotonic energy dependence of spin relaxation time

Magnetic impurities also evidenced by weak localization experiments

Phys. Rev. Lett. 110, 156601 (2013)

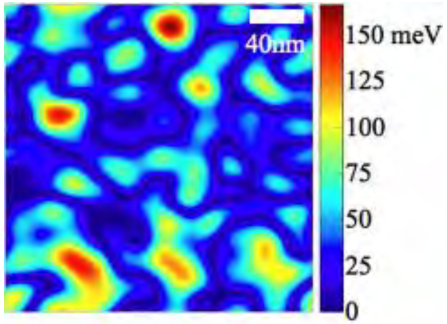
Able to fit SLG experiment from

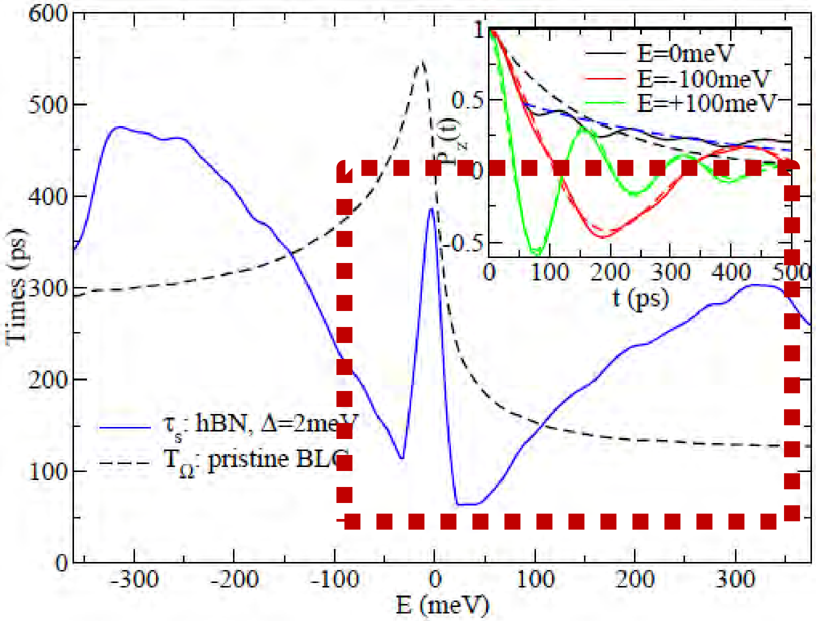
Wojtaszek, M., Vera-Marun, I.J., Maassen, T. & van Wees, B.J. Phys. Rev. B ***87,*** *81402 (2013)*

Recent spin relaxation mechanism: reinforced Dyakonov-Perel

Only Dyakonov-Perel mechanism and e-h puddles (no magnetic impurities)

Non-monotonic energy dependence of τ_s for high-quality bilayer graphene

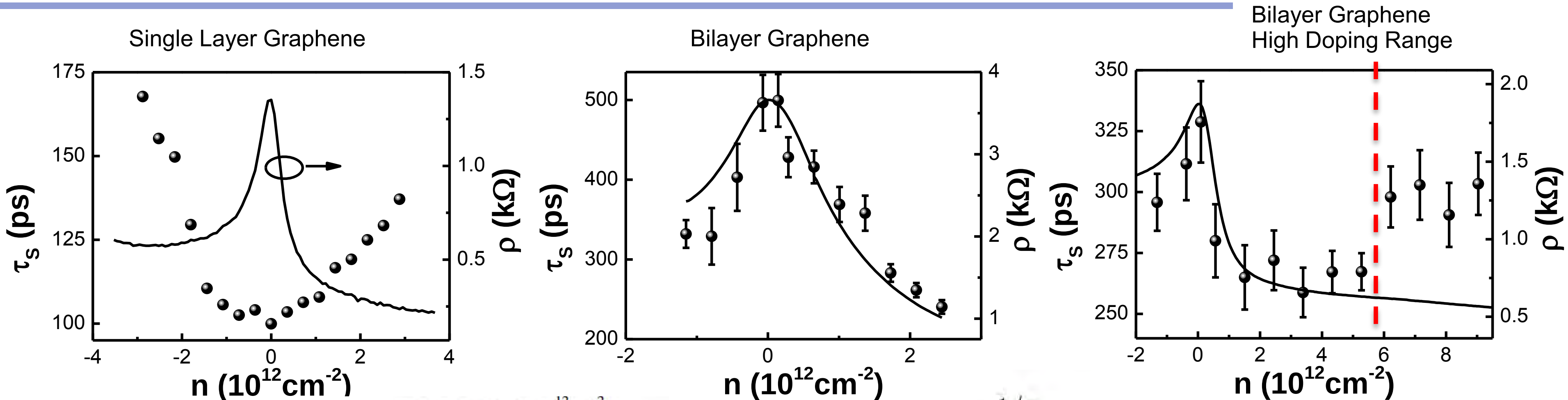


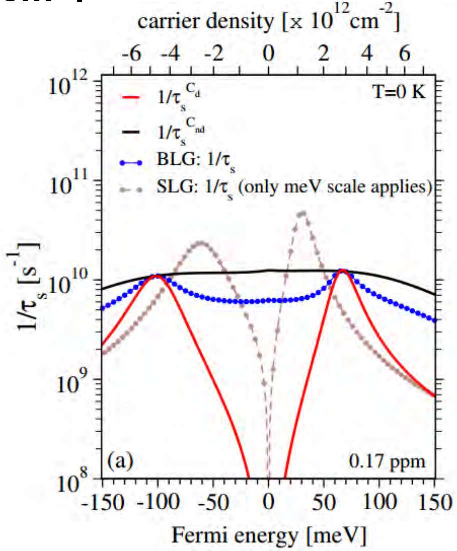


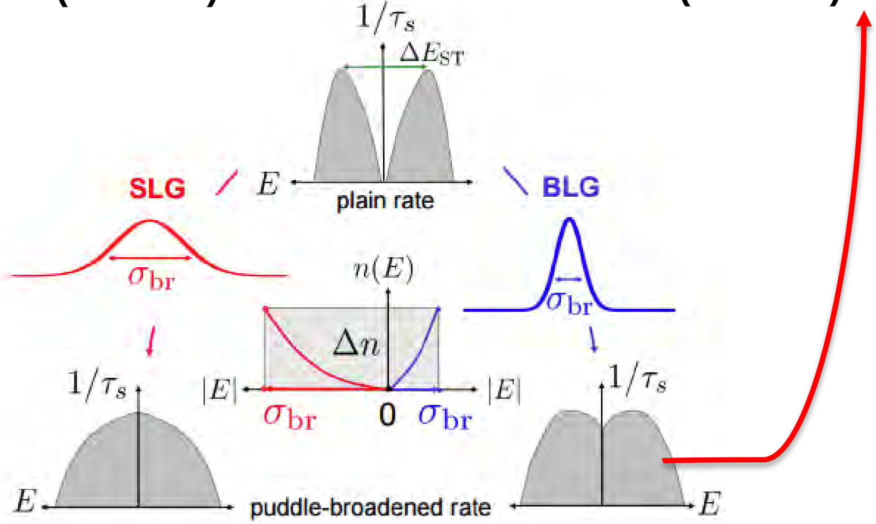
Van Tuan, D., Adam, S. & Roche, S. Spin dynamics in bilayer graphene: Role of electron-hole puddles and Dyakonov-Perel mechanism. Phys. Rev. B 94, 041405(R) (2016)

*Van Tuan, D., Ortmann, F., Cummings, A. W., Soriano, D. & Roche, S. Spin dynamics and relaxation in graphene dictated by electron-hole puddles. Scientific Reports **6,** 21046 (2016)*

Spin Transport in BLG







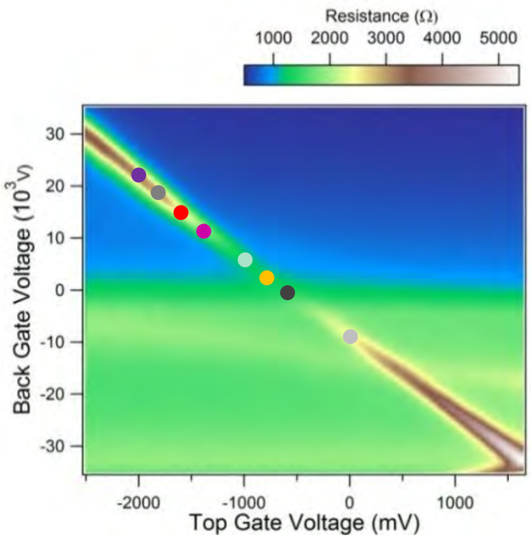
Kochan, D., Irmer, S., Gmitra, M. & Fabian, J. Resonant Scattering by Magnetic Impurities as a Model for Spin Relaxation in Bilayer Graphene. Phys. Rev. Lett. ***115,*** *196601 (2015).*

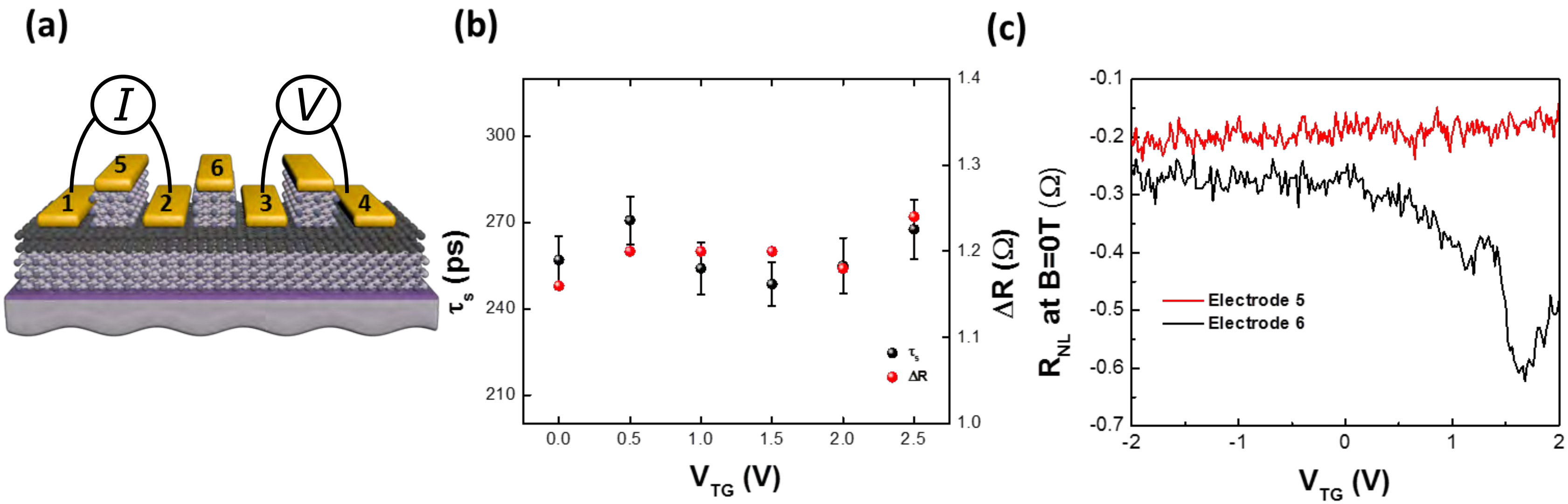
Spin Transport in dual-gated BLG

μ ≈ 24000 cm²/Vs @ 2K

Local control of band-gap (#5) has no affect on nonlocal spin transport

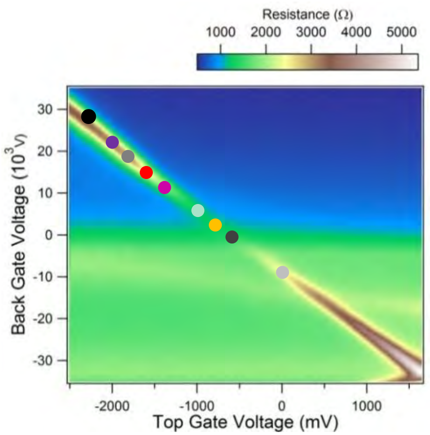
A gap in the nonlocal region (#6) modulates the spin signal → spin FET

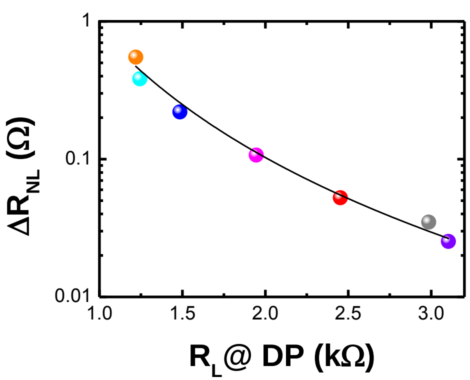


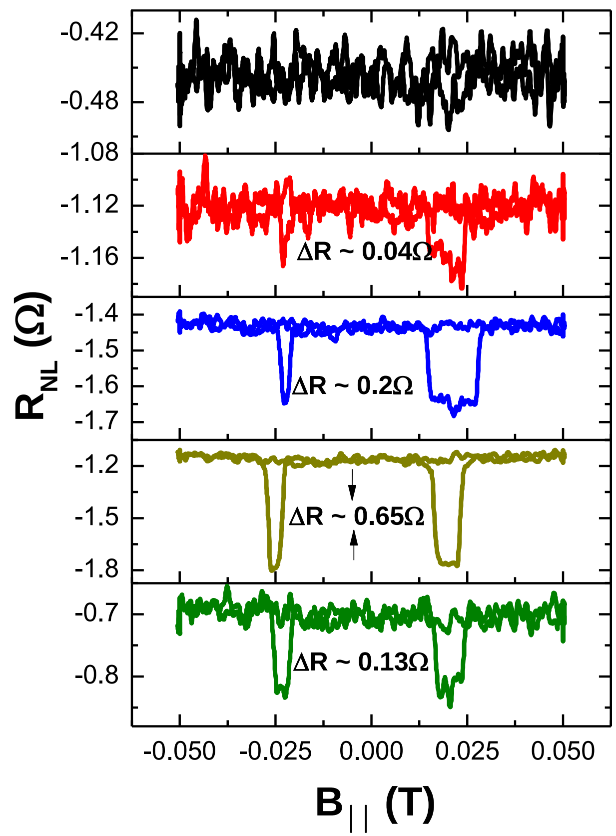


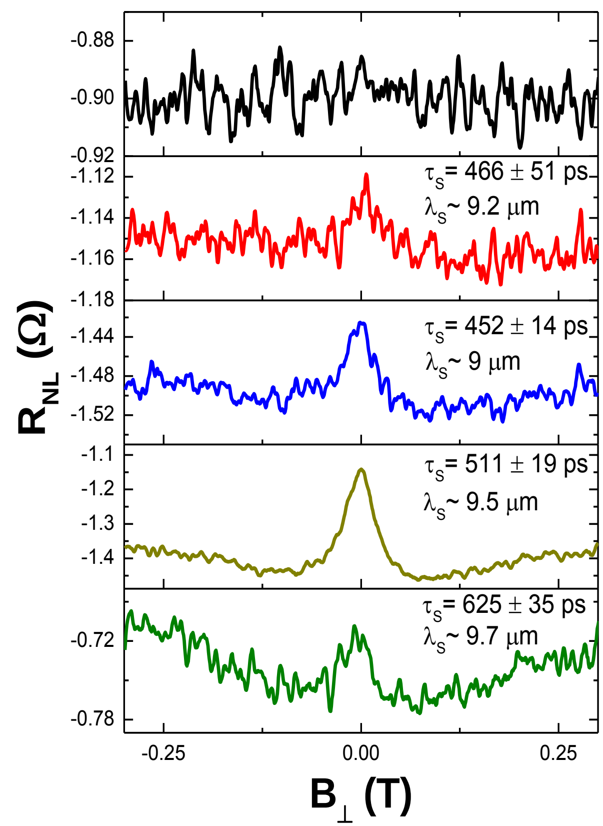
Spin Transport in dual-gated BLG

- Modulation >10x spin FET in presence of band-gap @ 2K
- Large λ ~ 10 μm, τ ~ 0.5 ns → no additional spin scattering
- μ ≈ 24000 cm²/Vs (best quality)









Take-home message (1)

Key role of residues & adsorbates, not substrate or contacts

First observation of non-monotonic energy dependence for BLG spin lifetime, consistent with recent models

Spin signal modulation > 10x via FET action

A. Avsar, I. J. Vera-Marun, J. Y. Tan, G. K. W. Koon, K. Watanabe, T. Taniguchi, S. Adam, and B. Ozyilmaz, "Electronic Spin Transport in Dual-Gated Bilayer Graphene," NPG Asia Materials 8, e274 (2016)

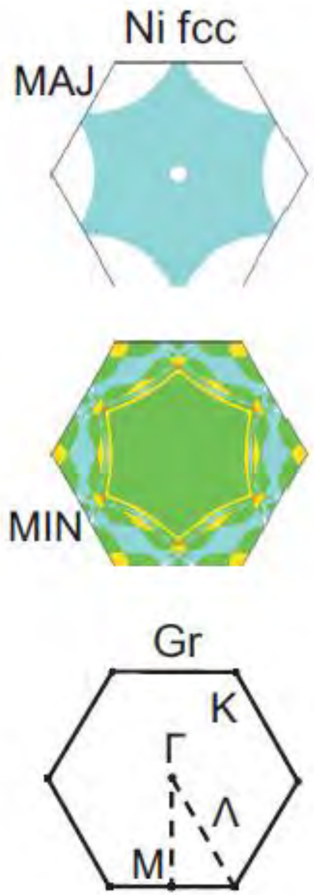


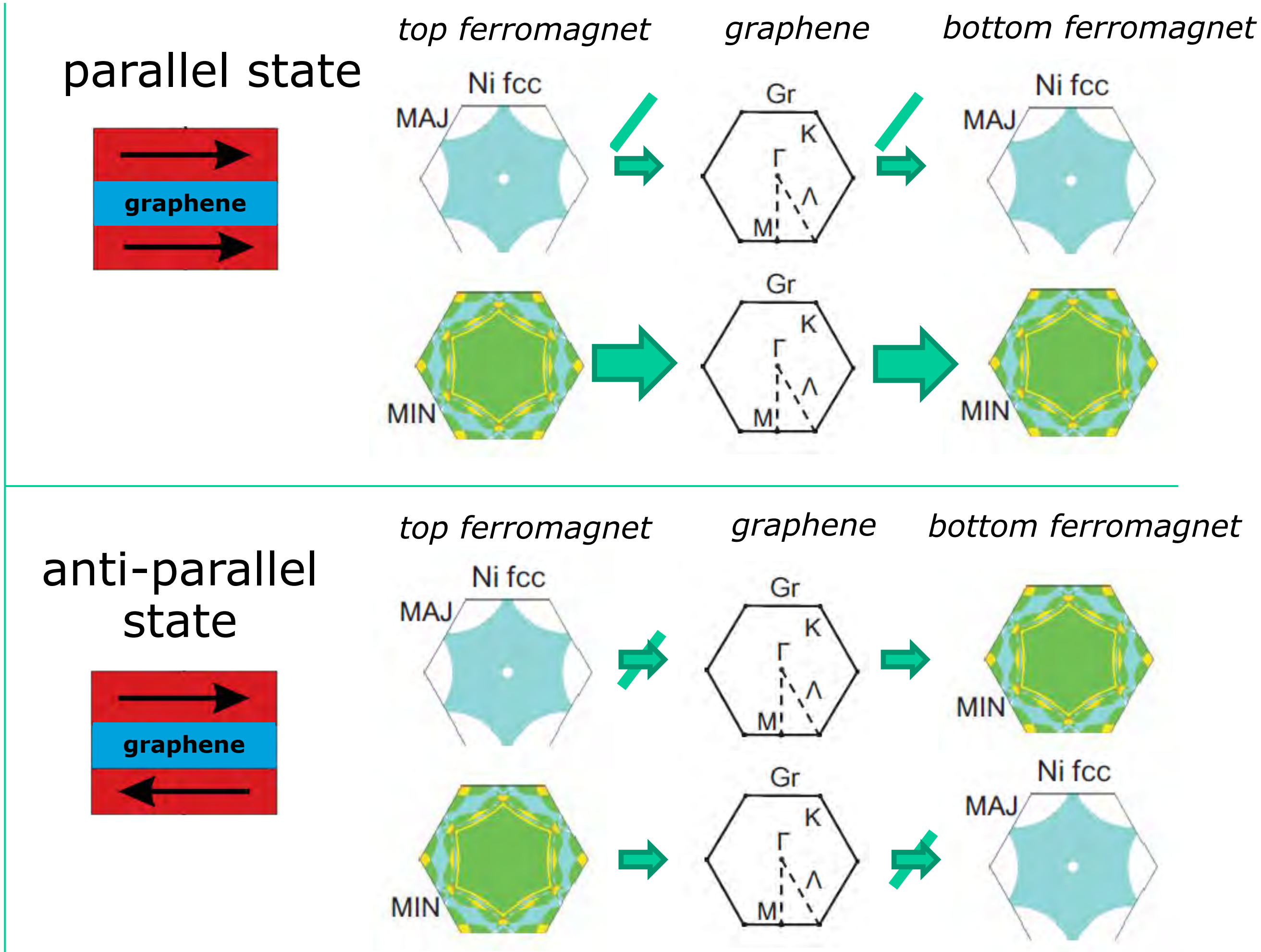


NUS National University of Singapore


NIMS 国立研究開発法人 物質・材料研究機構 National Institute for Materials Science

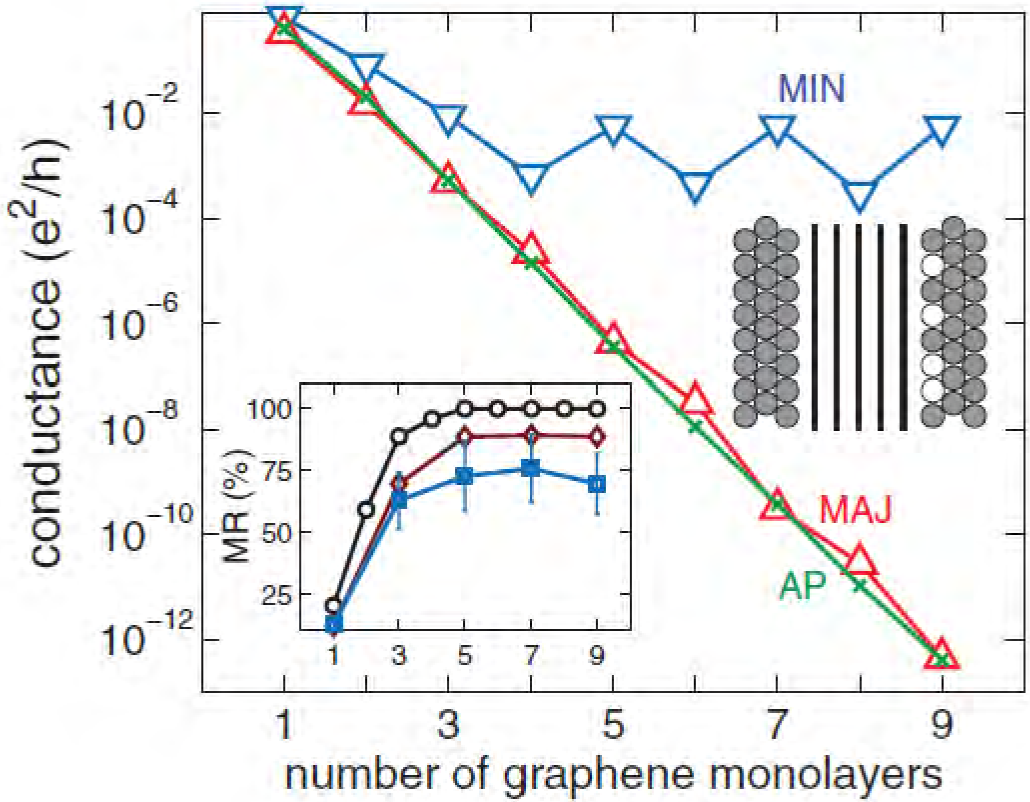
Vertical devices: perfect spin filter?





V. M. Karpan et al., *PHYS. REV. LETT. 99, 176602 (2007) and PHYS. REV. B 78, 195419 (2008)* (Co or Ni, graphene spacers)
Oleg. V. Yazyev and A. Pasquarello, *PHYS. REV. B 80, 035408 (2009)* (Co, Ni or Fe, graphene or BN spacers)

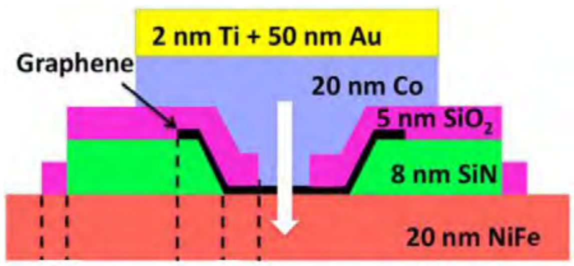
Vertical devices: perfect spin filter?

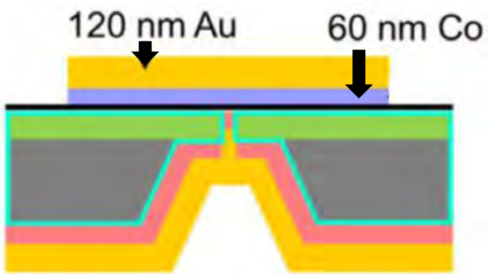


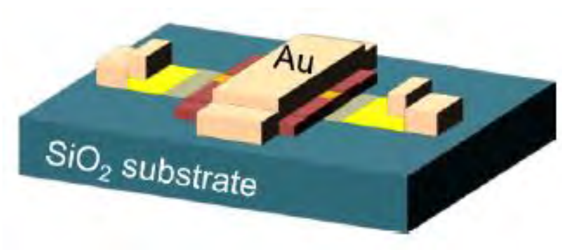
✓ 100% MR expected for few-layer graphene

V. M. Karpan et al., *PHYS. REV. LETT. 99, 176602 (2007) ; PHYS. REV. B 78, 195419 (2008)*

Earlier experiments: monolayer spacer





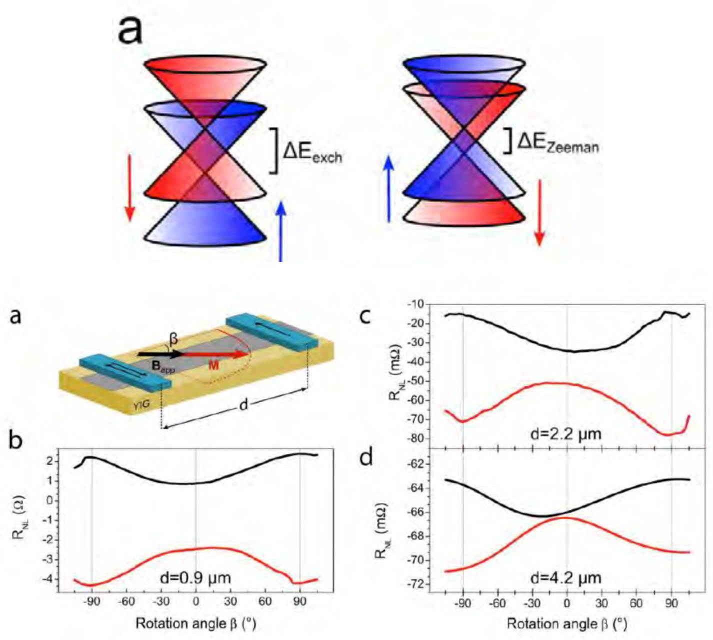


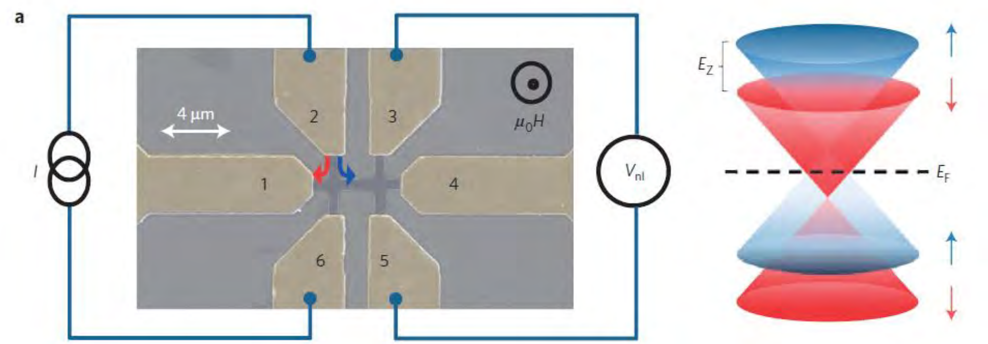
bottom-up fabrication	suspended membrane	'flip-transfer' method
~50 kΩ·μm²	~4 Ω·μm²	~0.2 Ω·μm²
tunneling, symmetric	tunneling, asymmetric	linear, metallic
MR: 2%	MR: 0.8 – 3.4%	MR: 0.3 - 4.6%

magnetoresistance
far below theoretical predictions

Left to right:
E. Cobas et al. *(Naval Res. Labs), NANO LETT. 12, 3000-3004 (2012) (possible oxidation of the ferromagnet)*
Wan Li et al. *(Cornell), PHYS. REV. B 89, 184418 (2014) (no oxidation)*
Jae-Hyun Park and Hu-Jong Lee, *PHYS. REV. B 89, 165417 (2014) (no oxidation)*

Proximity-induced spin splitting predicted and observed experimentally





~0.2T B_{exch} for graphene on YIG from lateral spin transport

J.C. Leutenantsmeyer et al,
2D Materials 4, 014001 (2017)

>14 T magnetic exchange field in graphene on EuS seen from spin Hall effect

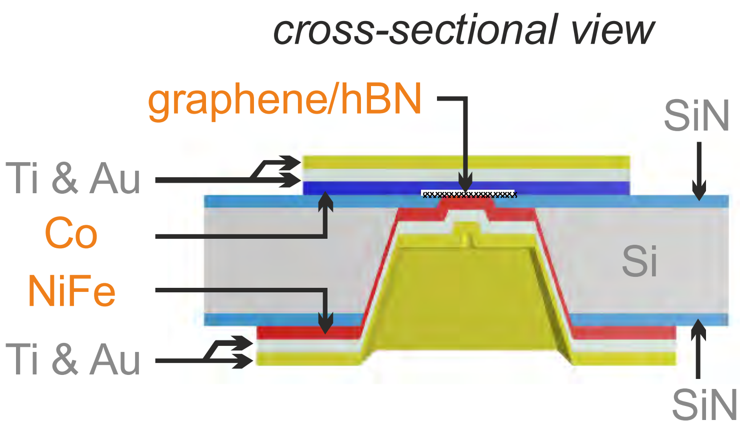
P. Wei et al, *Nature Mater.* DOI: 10.1038/NMAT4603

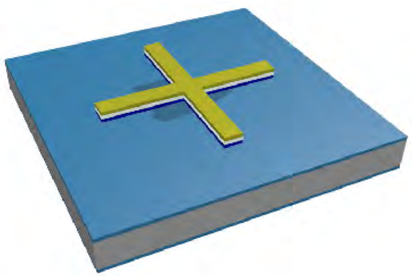
✓ theory predicts ~50-80 meV spin splitting in graphene in proximity to ferromagnets

Yang, H. X. *et al. Phys. Rev. Lett.* **110**, 046603 (2013).

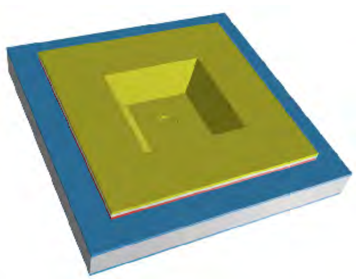
✓ expect that the combined effect of doping and proximity-induced spin splitting will determine FM/graphene/FM device behaviour

Vertical FM-graphene-FM junctions with 1 to 4 layers of graphene

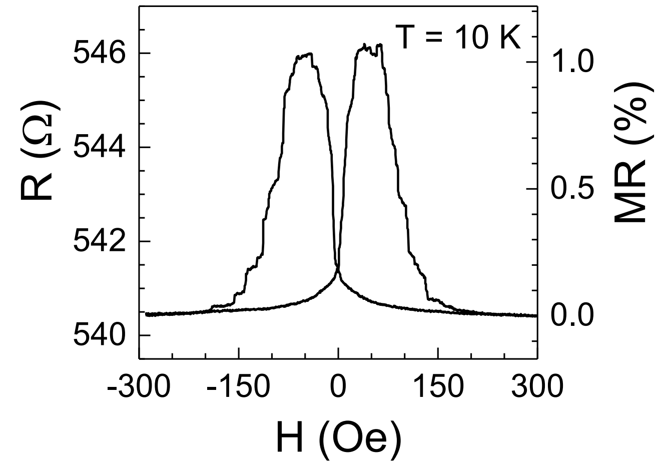


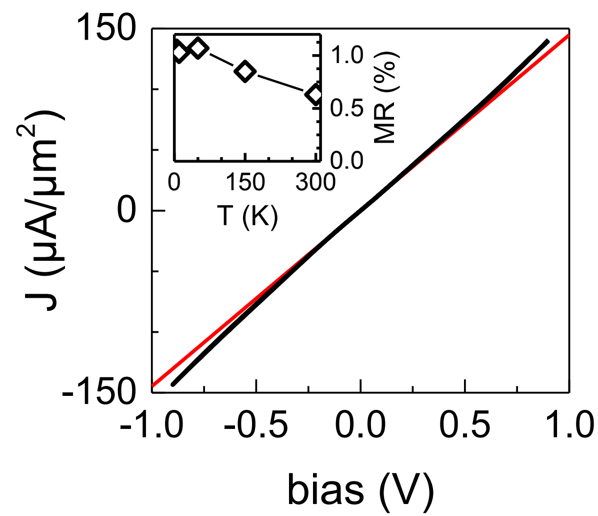


top view



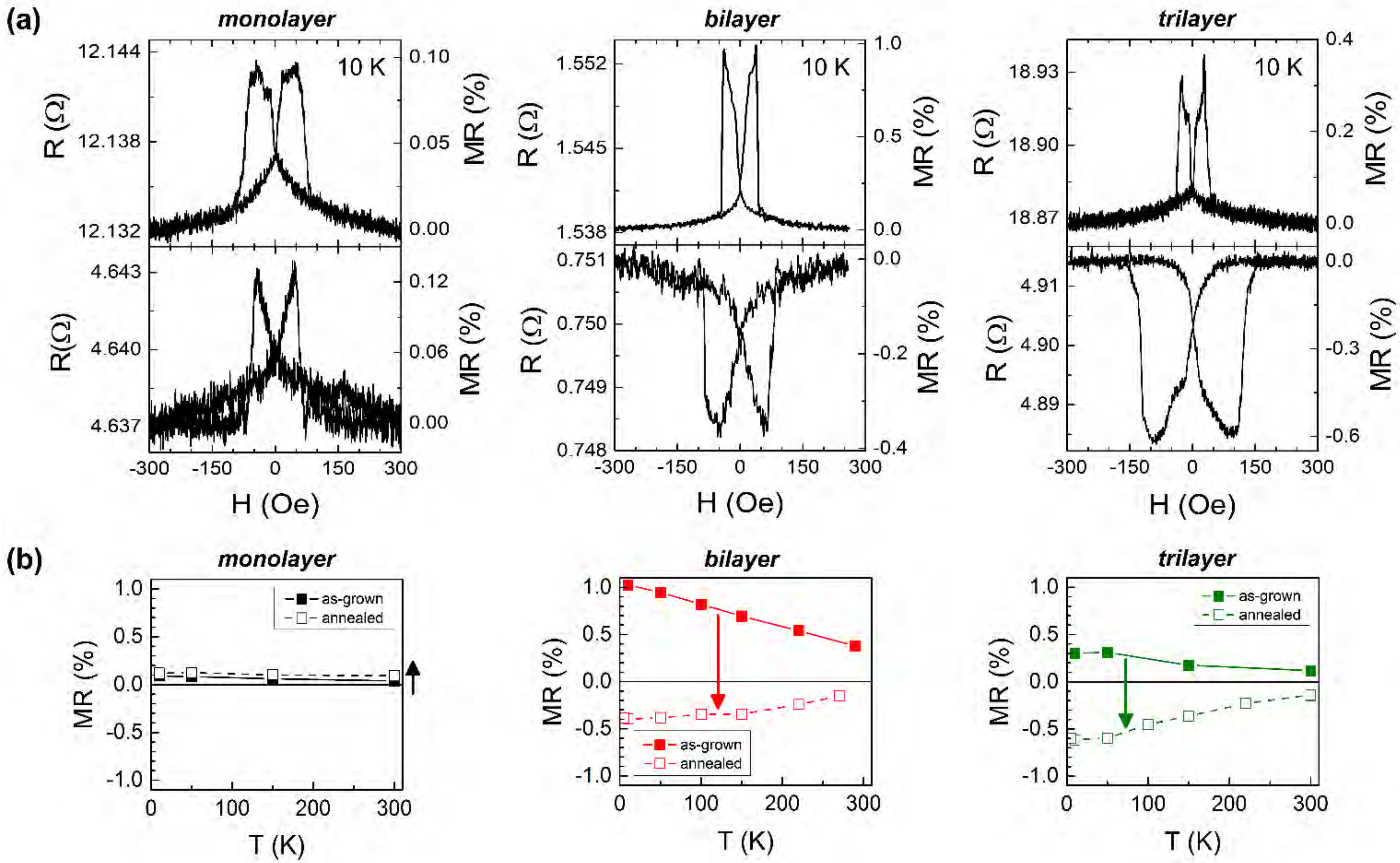
bottom view





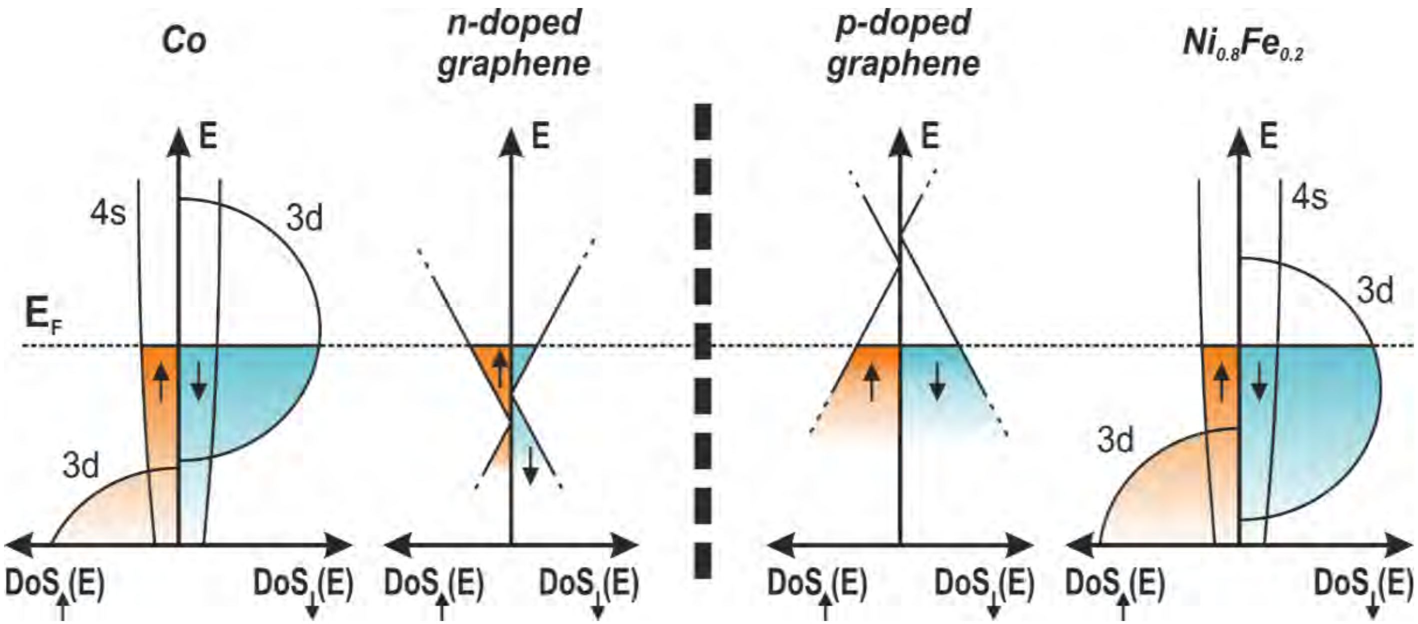
- ✓ same device architecture, same junction dimensions etc, only change the number of graphene layers
- ✓ tested with BN as a std barrier ~10% P

Different behaviour for mono and bi/tri-layers



- ✓ monolayer graphene: good spacer but small MR, similar to earlier studies;
- ✓ Bi- and trilayer: MR INVERSION after optimizing the FM/G contact

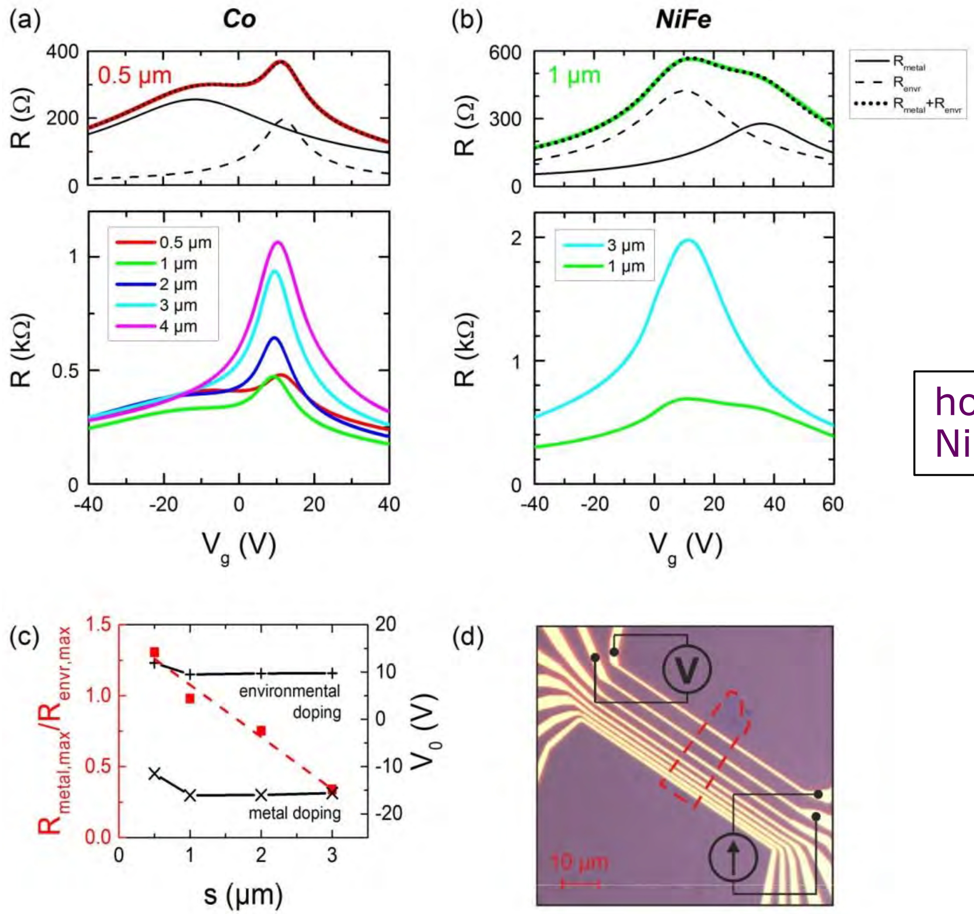
Graphene layers adjacent to different FM metals become different weak ferromagnets



experimental data consistent with the combined effect of doping and proximity-induced spin splitting

What about doping from the metal and proximity-induced spin splitting?

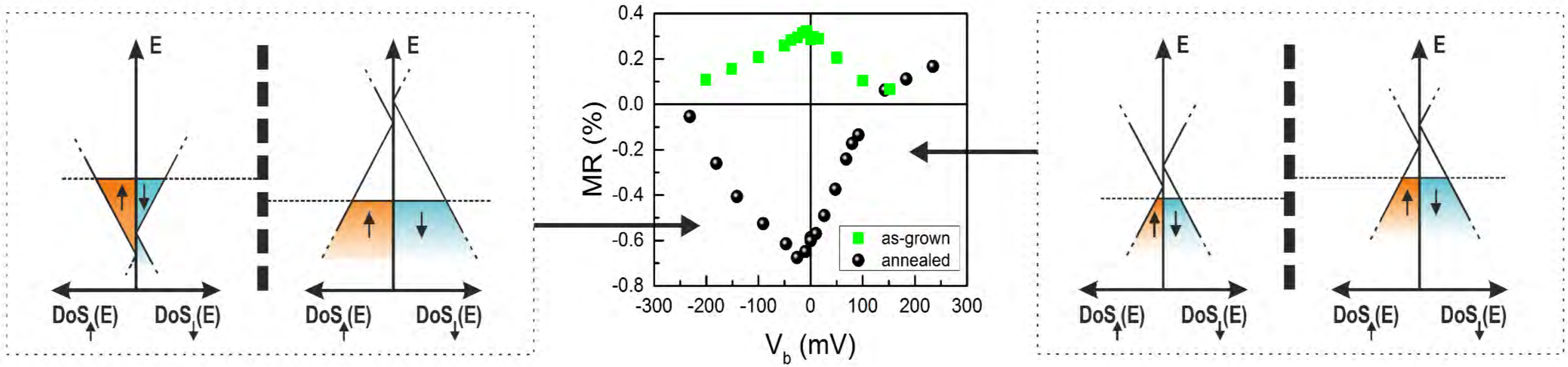
electron doping by Co



hole doping by NiFe

- ✓ doping of graphene by metal contacts is well known
- ✓ doping by Co and NiFe confirmed in our experiments

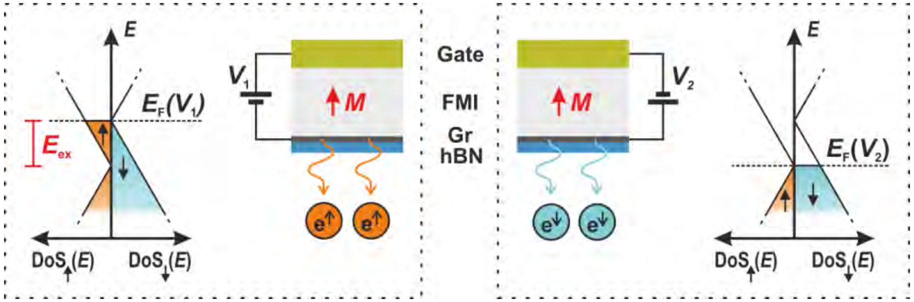
Graphene layers adjacent to different FM metals become different weak ferromagnets



- ✓ spin inversion back to positive MR under small bias, ~100 meV
- ✓ corresponds to the Fermi level shift due to doping by Co

Take-home message (2)

- monolayer graphene acts as efficient vertical spacer but does not provide significant MR
- bi- or tri-layer graphene: layers adjacent to FM electrodes become weak ferromagnets determining device behaviour
- *implication:*



Pablo Asshoff
Jose Sambricio
Artem Mishchenko
Andre Geim
Irina Grigorieva

Aidan Rooney
Alexander Rakowski
Sarah Haigh
Sergey Slizovskiy
Ernest Hill
Vladimir Falko

Asshoff, P. *et al.* Magnetoresistance of vertical Co-graphene-NiFe junctions controlled by charge transfer and proximity-induced spin splitting in graphene. *2D Mater.* (2017)

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Thank you for your attention